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Microstructural Alteration of Hydrocarbon Contaminated Permafrost Affected Soils at the Caribou - Poker Creeks CRREL Research Watershed: Implications for Subsurface Transport

ABSTRACT

The thermodynamic conditions within the seasonal frozen active layer overlying permafrost in the Caribou-Poker Creeks Research Watershed in Alaska are such that there is continuing translocation of water, ice and the displacement of soil particles. The introduction of immiscible hydrocarbon compounds from two large scale winter and summer experimental crude oil spills into this dynamic porous medium results in microstructural changes that take place as a function of cryogenic process and contaminant concentration. Optical and scanning elecron microscope observations reveal evidence of changes in soil morphology. Reorganisation of silt and clay size minerals and organic particles have resulted in changes in aggregation and interaggregate porosity in a histic pergelic cryaquest. The degree of interaggregate porosity increases as a function of hydrocarbon concentration, specifically volatiles and as a function of the soil profile. Hydrocarbon concentrations were observed to decrease as a function of depth in the O1,A1 and C1 horizons for all the sites, including the selected control site situated between the winter and summer experimental oil spills. The modifications of the microstructure change macroscopic properties (thermal, hydraulic, and mechanical), and this leads to modifications in terrain which become more marked over years. Remote sensing techniques will be important in the prediction and verification of contaminant movement.

INTRODUCTION

Following oil, gasoline or other hydrocarbon contamination it is important to know what will happen to various hydraulic, thermal and geotechnical properties of soils and corresponding ground water. Freezing soils behave differently to unfrozen soils; and little information is available concerning the interaction of hydrocarbon contaminants with freezing or thawing soils found in the active layer above permafrost. The majority of surface hydrocarbon spill studies have addressed what impacts petroleum spills have on vegetation and the depth of the active layer (Collins et al 1993). While many studies report the rate of contaminant spreading on the surface, these reports are generally descriptive (oil present versus not present) and are limited to the short term migration (1-5 years) through the active layer.

In 1976 two large scale experimental crude oil spills were carried out in Caribou-Poker Creeks Research Watershed (Figure 1) located 48 km north of Fairbanks, Alaska by CRREL researchers Sparrow et al (1978). The experimental spills each consisted of 7600 litres of Prudhoe Bay crude oil and took place in the winter (February 1976) and summer (July 1976) to test what happened when crude oil was spilled on permafrost-underlain black spruce forest of interior Alaska. In 1990 these spill sites were revisited by CRREL research personnel to assess the long term effects on permafrost and vegetation, as well as changes in oil chemistry.

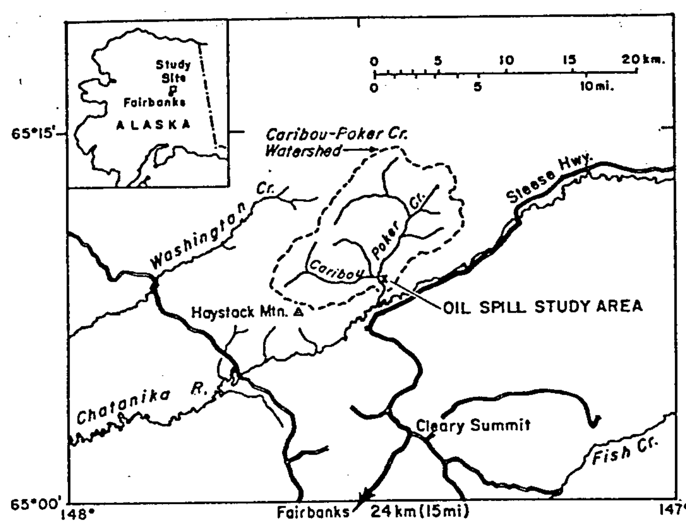


Figure 1: Caribou-Poker Creeks Research Watershed and experimental crude oil spill site

For the original study (Johnson et al, 1980) a distribution map of the oil in each of the two spills was prepared showing the extent of the spills and areas where oil was visible on the surface. Collins (1993) expanded the original study to include subsurface observations in 1990 (Figure 2) using wooden dowels pushed into the soil to visually inspect for the presence of hydrocarbons. In general, the thickness of the zone within the soil profile affected by hydrocarbon contamination was observed to thin out as a function of distance down slope of the points of release. The vertical distribution of subsurface crude oil was generally beneath the 01 and 02 horizons characterised by living moss and peat layer and contained within the A1 and C1 horizons characterised by mineral soil to a depth of between 20 to 30 cm below surface. At the upper end of the slope (3.5 m from point of release) maximum depth of oil penetration was observed to be 15 to 21 cm. At 34 m down slope the oil affected soil horizons extended deeper to between 25 to 30 cm. The study by Collins (1993) found it was difficult to ascertain whether or not the oil had moved vertically any deeper at either spill site because a zone of water saturation was encountered between 40 cm to 60 cm beneath the surface in 1990.

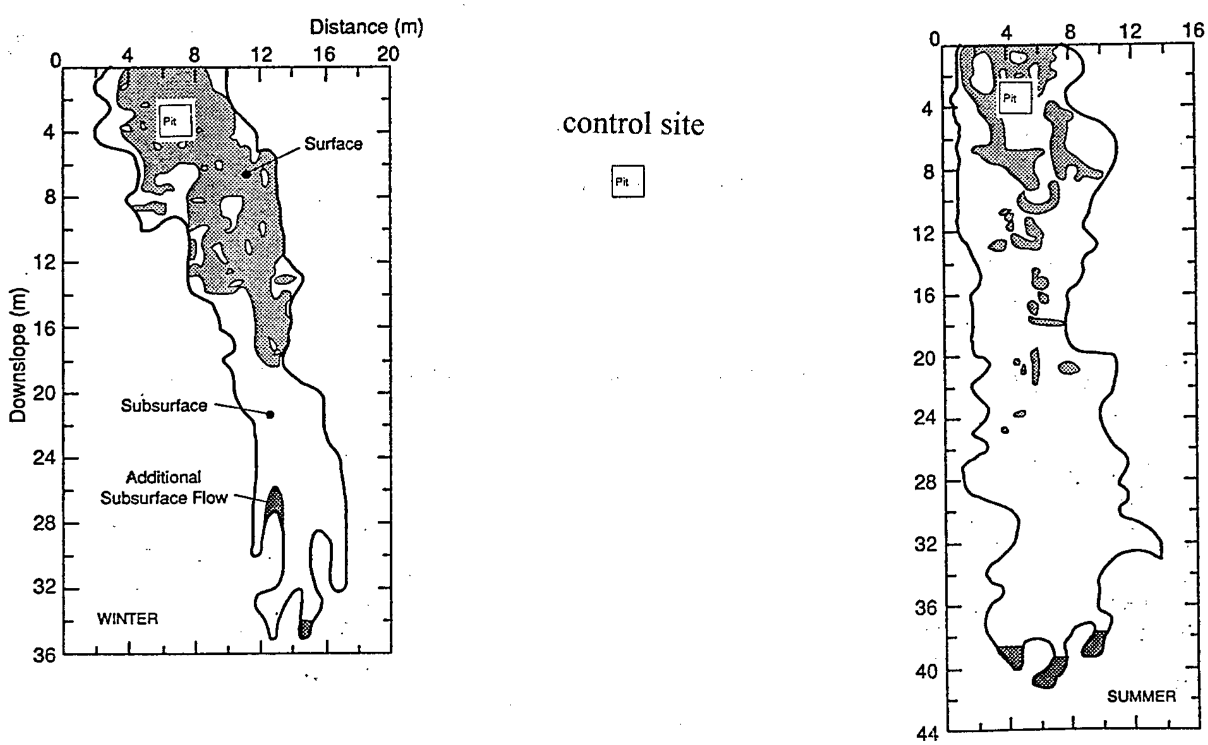


Figure 2: Winter and summer experimental spills and location of soil sampling pits
Distance between spill zones not to scale

CONTAMINANT TRANSPORT IN PERMAFROST AFFECTED SOILS

The ease with which any fluid can be transported through soil is dependent upon the properties and relative volumes of all fluids present. In seasonally frozen soil such as those in the active layer at Caribou-Poker Creeks, the water to hydrocarbon ratio will control the relative permeability of the soil to each of the fluids. Increasing hydrocarbon saturation of soil for example, should decrease the permeability of the soil to water as soil pores and particle surfaces become occupied by oil. This decreases the channel widths available for the migration of water and hydrocarbons (White and Williams, 1999).

Microstructural laboratory studies (White and Coutard, 1999) and field work in permafrost terrain (White, 1999) have revealed the dynamic nature of permafrost-affected soils (cryosols) when they come into contact with contaminants. Significant increases in hydraulic conductivity of an experimental silt took place when low concentrations of diesel fuel were introduced into the soil water. A four-fold increase in hydraulic conductivity (2.9×10^{-4} cm s^{-1} to 9.8×10^{-4} cm s^{-1}) relative to uncontaminated silt exposed to four freeze-thaw cycles were observed for hydrocarbon concentrations ranging between 50 to 200 ppm TPH (total petroleum hydrocarbons). When TPH values approach 1000 ppm hydraulic conductivity values were observed to decrease by an order of magnitude from 2.9×10^{-4} cm s^{-1} (uncontaminated silt) to between 5.3×10^{-5} cm s^{-1} to 8.48×10^{-5} cm s^{-1}.

These marked differences in hydraulic conductivity were explained by White and Coutard's 1999 observations on interparticle and inter-aggregate porosity. Inter-aggregate porosity (between aggregates) increased 25 to 29% for TPH concentrations of 10 ppm, and up to 33% with TPH concentrations of 100 ppm were measured. On the other hand, sharp declines in interaggregate porosity (10%) were observed to take place when TPH concentrations exceeded 1000 ppm.

When an organic contaminant at low concentration of 50 to 200 ppm enters the pore space of a soil containing clay minerals such as smectite, the organic molecules (which have a low dialectric constant) begin to replace the water molecules in the double layers that surround clay minerals. There is a tendency for the particles to move closer together and form aggregates as reported by White and Williams (1999) and White (1999). In contrast when organic contaminant concentrations exceed 1000 ppm a significant effective stress is created which may prevent the development of new macro porosity (between aggregates) by causing the soil to consolidate as a whole. The double layer surrounding the clay minerals undergo shrinkage, and there is a corresponding reduction in the overall permeability of the soil.

OBJECTIVES OF RESEARCH PROJECT

The two well-documented crude oil spills were made in the Caribou-Poker Creeks research watershed under summer, and winter, conditions. They provide a unique opportunity to examine insitu microstructural alteration of the active layer of a permafrost-affected soil and to determine what implications these changes have on sub-surface migration of contaminants. The research project reported in this interim report had two principle objectives:

1. To compare the microstructure of uncontaminated, seasonally frozen soils over permafrost with similar soils which have been contaminated by a crude oil hydrocarbon
2. To relate the identified microstructure to macroscopic properties such as hydraulic properties. From this to predict the rates of subsurface migration of the above noted contaminant.
3. To ascertain the effects thus produced in the terrain, and to examine the remote sensing of these effects.

FIELD RECONNAISSANCE, SEPTEMBER 1998

Field observations were carried out the week of September 19 by Dr. Les White, Senior Consultant, and Dr. Yvette Marchand, Research Fellow, both with the Scott Polar Research Institute at Cambridge University with the assistance of Dr. Charles Collins, CRREL in Fairbanks, Alaska. Undisturbed hydrocarbon contaminated soil samples from the summer and winter spill sites were obtained along with soil samples from a control site situated between the two spill sites (Figure 2).

The soils which are classified as histic pergelic cryaquest (US classification) are affected by permafrost which underlies the control active layer site at 65 cm beneath the surface. The cryosol profile is characterized by a 5 cm layer of moss and lichen above a 15 cm thick horizon of undecomposed peat (O1). This lies above a 5 cm horizon of decomposed black organic peat (O2) which lies on top of a 5 cm thick layer of dark grey silt (A1). Below the silt is a grey-brown mineral soil (C1) which extends down 300 cm to a schist bedrock.

The cryosols examined in the excavated sampling pits situated in the summer and winter spill sites were contaminated by crude oil. The presence of the hydrocarbons was readily discerned by sight (thin dark bands in the A1 horizon) and by the smell for the 01 and C1 horizons.

The vertical distribution of subsurface crude oil consisted of oil visible along some roots penetrating down from the O1 and O2 horizons into the A1 horizon. Oiled zones (bands) were visually discernable in the O2, A1 and C1 horizons with band thickness varying from 1 to 3 mm in thickness up to 10 to 15 mm thick.

Undisturbed soil samples were obtained from the three excavated sample pits situated in the summer and winter spill zones and a control site situated between these two zones. Kubiena box samples for micromorphology analysis of the soils and adjacent core samples were taken every 15 to 20 cm beginning at the surface and extending downward until a saturated zone was encountered within the C1 horizon. This zone of saturation was encountered at 80 cm below surface for the summer spill site and control site and at 120 cm below surface for the winter spill site. The mineral soils at depth become saturated within the active layer during thaw periods because the underlying permafrost is essentially impermeable. Table 1 presents physical property data including bulk density, moisture content and porosity for the core samples as a function of depth for all three sample pits.

MICROSTRUCTURAL OBSERVATIONS

Thin sections of soil were prepared from undisturbed samples after soil water and immiscible hydrocarbon contaminants had been removed and replaced by acetone and then subsequently impregnated with a polyester resin containing a fluorescent dye (Uvitex PB, Ciba-Geigy). The methodology for soil-water removal, sample impregnation, and thin-section preparation is widely documented, having been described by Fitzpatrick (1984).

The use of thin sections facilitates the description of the arrangement of soil particles and pores, and provides information on the particular features and how they are integrated with properties such as hydraulic conductivity. Morphology of the thin sections was described according to a glossary of micromorphology terminology (Fitzpatrick, 1984; Howes and White, 1991). Soil fabric descriptions were made from vertically oriented thin sections at 12 x magnification. This magnification showed the gross morphology that characterises the structure of the soil fabric.

Optical and scanning electron microscope (SEM) micrographs from undisturbed soil samples taken from the contaminated summer and winter spill sites and the selected control site (originally assumed to have been uncontaminated) are illustrated in micrographs Plate 1 to 23. They show clear and very distinct morphologies with major differences in soil aggregation and porosity. On close examination it is evident that there are two major factors explaining this diversity. Soils in the active layer are exposed to bi-directional freezing and thawing annually, and thus have been frozen and

thawed many times. Secondly, immiscible contaminants of different concentrations have a significant impact on pore water chemistry and dielectric constants which modify the microstructure.

Distinct gross morphologies, characteristic of contaminated soils, were observed to have developed in all the samples exposed to hydrocarbons including those sampled from the selected control site. Introduction of contaminants of low-water solubility such as hydrocarbons into a porous medium results in a two-phase flow system, each with its own effective permeability and thermodynamic characteristics. Micromorphological observations of thin sections prepared from contaminated and control sites for soil horizons O1 (Plates 1 to 3), A1 (Plates 7 to 9) and C1 (Plates 12 to 15) present in the active layer soils shows evidence of changes in soil aggregation both at the interparticle and interaggregate scale. All three soil horizons examined in the summer, winter and control sample pits were observed to have undergone microstructural alterations associated with the presence of immiscible hydrocarbon compounds in soil water surrounding mineral and organic particles. Total petroleum hydrocarbon (TPH) determinations (Table 1) confirm the presence of hydrocarbons in all three horizons for the three sample locations. TPH concentrations were observed to decrease as a function of increasing depth in all three soil profiles.

In the O1 horizon the morphology is characterised by moderately decomposed organic particles with inclusions of sphagnum moss fragmics. Organic fragments tend to be clustered together. Aggregation was associated with the presence of immiscible hydrocarbon compounds. Undecomposed peat which makes up the 01 horizon was observed to have become clogged by hydrocarbons (black film surrounding organics, Plates 1 to 3). SEM micrographs (Plates 4 to 6) reveal additional information on how the peat fibres have been affected by hydrocarbons. Peat which has a high absorption capacity associated with its high surface areas absorbs the hydrocarbons along its outer surfaces; its internal cellular structure, however, remains intact. Immiscible compounds present in the film water at the surface of particles and unfrozen soil water are responsible for lowering the dielectric constant of the soil water. This results in a tendency for the clay and silt size particles to move closer together and to form aggregates (Plate 20).

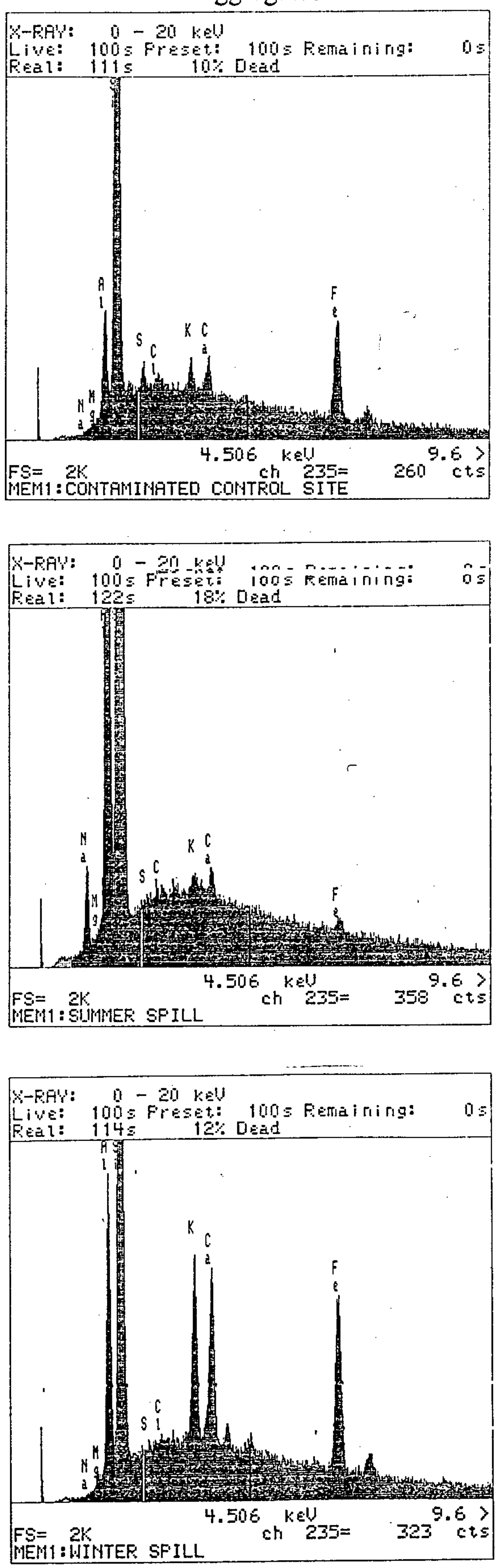
In the A1 horizon the morphology is characterised by dense soil fabric consisting of silt and clay size mineral material and fine organic material distributed throughout, evidence of faunal activity. Dark patches are discrete structural units (aggregates) in which contaminants have accumulated.

In the C1 horizon the morphology is characterised by planar pores in fine granular matrix often aggregated, forming mullgranoidic fabric components. Hydrocarbon contaminants have accumulated along the upper surfaces of planar pores.

In contaminated horizons A1 and C1, soil samples taken from the control, summer and winter spill sites revealed how clay size minerals have been affected by the presence of organic contaminants. The development of these "signature" structures such as aggregates (Plates 19 to 23) which are used to identify contaminated soil at the microscopic scale appear to confirm that cation exchange sites present on the surface and along the edges of the clay size minerals have become occupied by immiscible hydrocarbon compounds present in the soil water. The close packing of the particles within the aggregates results from the effective stresses that develop on the silt because of cryogenic processes along with the reduction of surface area of the clay-size minerals and organic particles as a result of hydrocarbon contamination. The formation of aggregates results in increasing macroporosity between the aggregates and an increase in the permeability of the soil following thaw.

It appears that contamination has also occurred at the 'control' site. Significant increases in the hydraulic conductivity account for the subsurface contamination of the O1, A1, and C1 horizons of the control site situated

Figure 3: X-Ray Diffraction Patterns for Soil Aggregates



between the summer and winter spill sites. Optical microscope observations (Plates 13 to 16) show particle aggregation that occurs adjacent to planar pores. Plate 13 shows a zone of compaction along the upper boundary of a planar pore. Hydrocarbon contaminants which appear black have accumulated along the upper surface of the pore. X-ray diffraction patterns (Figure 3) for soil aggregates sampled from all three sites confirm the presence of the element sulfur, an element present in Alaska crude oil used in the experimental spills.

HYDRAULIC CONDUCTIVITY OBSERVATIONS

In a two-liquid phase flow system such as that with soil water and crude oil the effective permeabilities are dependent on the saturation percentage of each fluid and the wettability of the soil with respect to these two fluids. When two fluids are in contact with a solid, one usually has greater affinity for the solid than the other. In permafrost affected soils (cryosols) such as the study sites histic pergelic Cryaquest (US classification) which contains clay size minerals, polar water molecules are attracted to negatively charged clay sized mineral surfaces more strongly than are non-polar organic molecules. In a water wet silty clay an organic liquid such as crude oil will generally be the non-wetting liquid. The movement of liquid contaminants and modification to the microstructure of a freezing soil is influenced by factors including temperature, temperature gradient, moisture content (above and below 0°C) and mineralogical composition. The permeability of the soil to the contaminant must relate closely to the soil structure. Equally important, the surface area of soil particles and aggregates and the geometry of pore space define the environment in which hydrocarbon breakdown will occur as a result of biological or chemical agents.

Significant increases in hydraulic conductivity of the Caribou Poker Creek silty clay soils were observed to have taken place (Table 1) when the crude oil and some of its weathered components were introduced into the O1 horizon (-15cm) and made their way through

to the A1 (-30 cm) and C1 (-40 cm) horizons. An increase in hydraulic conductivity (4.39 to 7.39 x 10^{-3} cm s^{-1}) was also observed for the O1 and A1 horizons of the summer spill site where TPH values range from 2.3 to 291 ppm and a three fold increase (4.47 to 4.69 x 10^{-3} cm s^{-1}) was observed for the O1 and A1 horizon of the winter spill site where TPH values ranged between 8.3 to 863 ppm. Corresponding porosity values for the horizons were also observed to have increased as a result of the formation of soil aggregate (Plates 19 to 23). An increase in hydraulic conductivity (2.25 x 10^{-3} compared to 1.56 x 10^{-3} cm s^{-1}) was observed to have occurred for the C1 horizon of the summer spill site. At depths of 60 cm below surface the hydraulic conductivity of the summer (6.77 x 10^{-5} cm s^{-1}) and winter (6.84 x 10^{-5} cm $s^{-1)}$ spill sites was observed to be lower by an order of magnitude compared to the control site (1.32 x 10^{-4} cm s^{-1}).

The marked differences in hydraulic conductivity can be explained by the observations on inter-particle and inter-aggregate porosity (White and Coutard, 1999). Plates 21, 22 and 23 are micrographs produced using scanning electron microscope. These plates illustrate that the degree of compaction of individual aggregates increased the interparticle porosity while the intra-particle porosity of the individual aggregates decreased. The close packing of the particles within aggregates results from the effective stresses that develop in the silty clay because of cryogenic processes along with the reduction of the effective surface area of the clay size minerals. TPH values for the summer and winter sites were observed to have decreased to barely detectible values of 1.8 to 1.9 ppm respectively at 60 cm below surface. The TPH values for the control site at a depth of 60 cm were observed to be quite elevated (comparatively) at 53 ppm and might help explain why the control site hydraulic conductivity is one order of magnitude greater. Subsurface transport of hydrocarbons through the soil horizons of the control site has occurred in more recent years. The elevated TPH concentrations would indicate that biodegradation has not occurred over the same timeframe as it has at both the summer and winter spill sites.

RESULTING TERRAIN MODIFICATIONS AND REMOTE SENSING

Changes in microstructure of the kind demonstrated, have significant effects on the macroscopic properties of the soil. These effects are particularly significant in two respects. Firstly, the thermal properties of the soil are significantly changed. Associated with this will be changes in the depth of active layer, and in the temperature regime as a function of depth and time. Secondly, change in the hydraulic properties affects the movement of water (and, in the event, contaminants) and associated phenomena such as drainage, the amount of frost heave, and soil strength. Together it is the thermal, thermodynamic and hydraulic behaviour of the soils that gives rise to the ground surface features, the terrain, characteristic of the cold regions.

These surface features include slope movement phenomena, subsidence (including thermokarst) and development of various forms of patterned ground (Williams and Smith 1989). Associated with this, there will also be modifications in the species composition of the vegetation. The changes are easily recognised by the experienced observer on the site. Once conditions are disturbed (for example, by contamination, but also by 'natural' events), the changes occur progressively, often over tens or even hundreds of years.

At a spill site or other contaminated sites, these progressive changes are also a key to prediction of future behaviour of the contaminant and thus can provide a basis for designing appropriate remedial responses.

A review of the literature and an earlier visit showed that a small-scale spill site, specifically the Caribou-Poker Creek CRREL experimental oil spills site, would give much information of the changes in terrain and vegetation following the addition of a contaminant. In fact, this site is apparently the best documented and longest running experimental site in North America. It

has been monitored (and various thermal and other conditions measured) on a regular basis, from its inception in 1976. It provides a unique opportunity for the study of the effects described above.

White and Marchand visited the site for the present project and observed the changes in vegetation and terrain, that have taken place as a result of the spills, of which there were two, one in the winter, the other in the summer. In Marchand's case the visit to Alaska was part of a broader visit, which included the New Hampshire laboratories os USACRREL, and the Ottawa laboratories of the Geotechnical Science Laboratories, Carleton University.

Compared with the sites of accidental oil spills in Russia and elsewhere (Marchand and Rees, 1999; Marchand and Rees, 2000; Marchand 2000), the Caribou-Poker Creek site is small indeed. Vegetation changes were clear, and there was some modification of terrain. Hand samples reveal different stages of breakdown of the oil - clearly recognised by smell. The small site, being rather uniform in morphology and soil, exposure etc., does not show the range of modifications to be expected over larger areas. However, modifications in depth of seasonal thaw and resultant changes in subsurface drainage, aided by the structural modifications to the soils described in previous sections, could be mapped out given sufficient time, and there is already a significant quantity of observations.

The size of the site proved too small for significant interpretation by remote sensing imagery, although it is likely that some further interpretation will be possible in future years as precision increases. The importance of the site lies in the possibility of detailed interpretations being made of the changes that are taking place in the ground and consequently in the terrain, following from the microstructural modifications revealed by the soil analyses. Information in such detail is not available from any of the much larger sites, in Russia, which are being examined concurrently by remote sensing, under several contracts held by SPRI. The latter work has shown that effects of contamination on the vegetation cover are readily visible if the area is large enough. The species composition, which is more relevant than biomass as an indicator of subsurface modification, is also presently not easily distinguished by remote sensing.

CONCLUSIONS

Micromorphological and scanning electron microscope observations carried out on the active layer soils overlying permafrost exposed to two large scale crude oil spills conducted in 1976 revealed the dynamic nature of contaminant interaction. The cumulative effects of translocation of water, immiscible hydrocarbon components and ice associated with bi-directional freezing and the sorption and retention of hydrocarbon compounds along the surfaces of clay sized minerals and organic material is responsible for significant changes in soil aggregation. Intraggregate porosity was observed to increase resulting in significant increases in hydraulic conductivity. These increases are responsible for the subsurface transport of immiscible hydrocarbon contaminants through the O1, A1, and C1 horizons.

This subsurface transport has apparently been responsible in more recent years for the contamination of the selected control site situation between the winter and summer spill zones. Additional field sampling should now be undertaken to collect soil samples from an uncontaminated control site situated up slope from the two large scale spill zones and to evaluate the spatial extent of the subsurface migration of hydrocarbon contaminants between the original summer and winter spill zones.

REMOTE SENSING

Observations in the field at the Caribou-Poker Creek site showed the effects of contamination after more than two decades on the vegetation cover and its species composition and also on the form and nature of the surface layers more generally. Remote sensing is, at present, still barely capable of revealing these changes when the area affected is as small as that at the Caribou-Poker Creek site. The effects

there, however, are an excellent analogue for the large spills that have occurred in Russia and the neighbouring republics, and which are indeed recognisable in current remote-sensing images. With the gradual improvement in remote sensing imagery, and a better understanding of the processes, such as may be gained from intense monitoring and further investigations at the Caribou-Poker Creek site, it will be possible to apply remote sensing to observing and then to predicting the course of changes due to contamination. Remote sensing will then be an important part of an integral strategy for the devising of appropriate and cost-effective bioremedial or other responses.

ACKNOWLEDGEMENTS

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TABLE 1: CARIBOU - POKER CREEK WATERSHED

CONTROL SITE

Depth in Active layer (cm)	Bulk Density g/cm^3	Moisture Content %	Porosity %	Hydraulic Conductivity K_s(cm s^{-1})	TPH (ppm)
15	1.17	69.5	77.2	1.69×10^{-3}	326
30	1.39	35.8	37.8	1.38×10^{-3}	218
40	1.23	30.8	34.2	1.56×10^{-3}	172
60	1.41	37.9	38.9	1.32×10^{-4}	53
80	1.33	17.2	29.6	1.61×10^{-5}	1.2

SUMMER SPILL SITE

Depth in Active layer (cm)	Bulk Density g/cm^3	Moisture Content %	Porosity %	Hydraulic Conductivity K_s(cm s^{-1})	TPH (ppm)
15	1.17	90.1	100	7.32×10^{-3}	291
30	1.59	33.9	36.1	4.39×10^{-3}	2.3
40	1.57	30.5	33.0	2.25×10^{-3}	1.3
60	1.52	37.9	42.0	6.77×10^{-5}	1.8
80	1.02	29.5	30.8	1.12×10^{-5}	2.5

WINTER SPILL SITE

Depth in Active layer (cm)	Bulk Density g/cm^3	Moisture Content %	Porosity %	Hydraulic Conductivity K_s(cm s^{-1})	TPH (ppm)
15	0.83	52.1	87.2	4.69×10^{-3}	863
30	1.26	51.3	54.7	4.47×10^{-3}	8.3
40	1.57	33.0	35.6	1.44×10^{-3}	1.4
60	1.62	25.2	28.2	6.84×10^{-5}	1.9
80	1.58	36.2	37.8	5.7×10^{-5}	2.1
100	1.55	24.8	35.3	3.5×10^{-4}	0
120	1.32	28.0	47.0	9.67×10^{-4}	0

O1 Horizon Undecomposed Peat, 15 cm beneath surface

Optical Microscope (*frames are 12 mm wide*)

Plate 1: Control Site

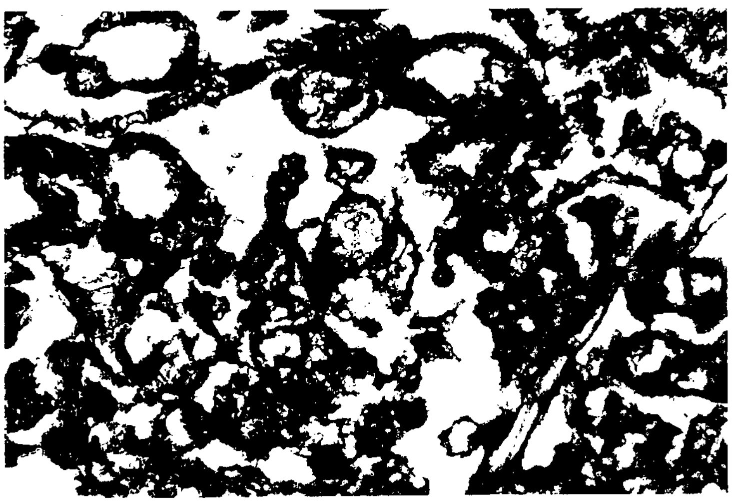

Plate 2: Summer Site

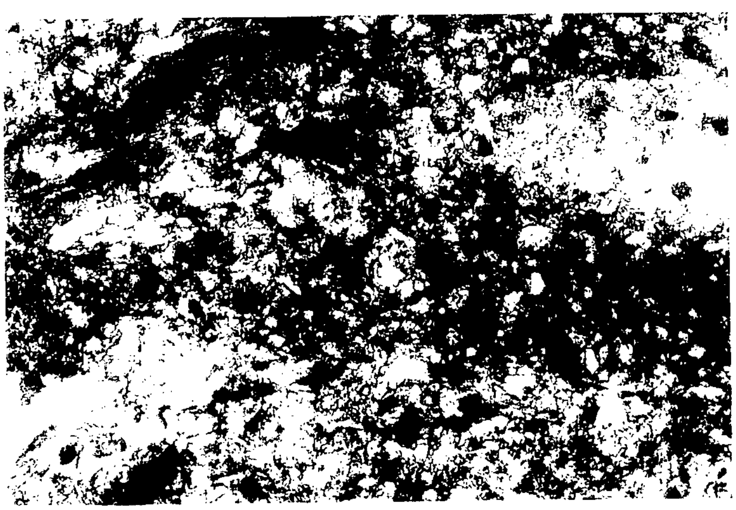

Plate 3: Winter Site

SEM

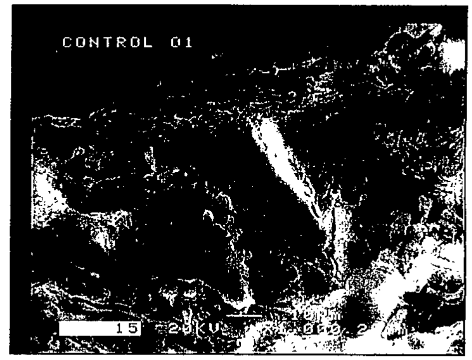

Plate 4: Control Site

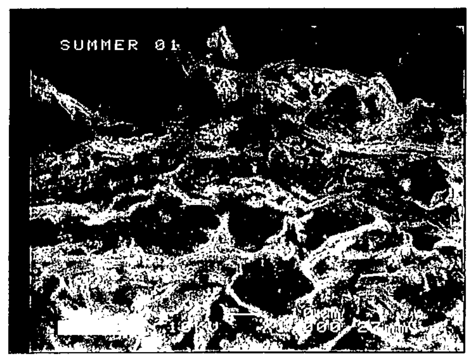

Plate 5: Summer Site

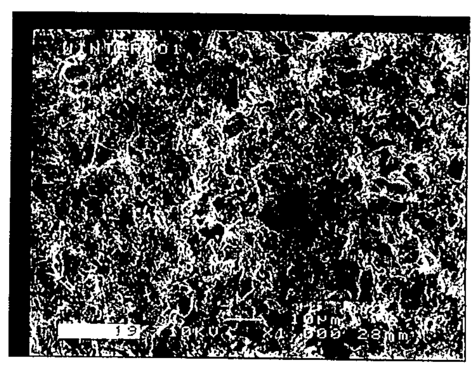

Plate 6: Winter Site

A1 Horizon Dark Grey Silt, 30 cm beneath surface

Optical Microscope *(frames are 12 mm wide)*

Plate 7: Control Site

Plate 8: Summer Site

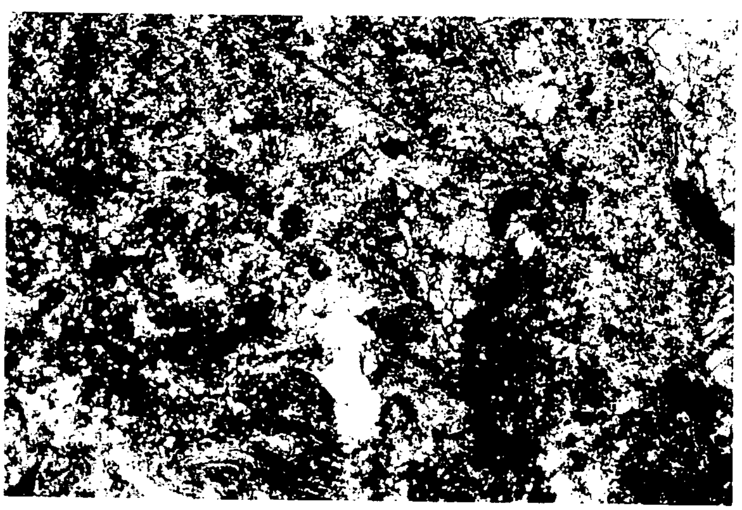

Plate 9: Winter Site

SEM

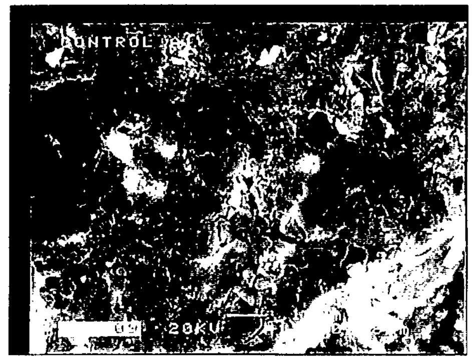

Plate 10: Control Site

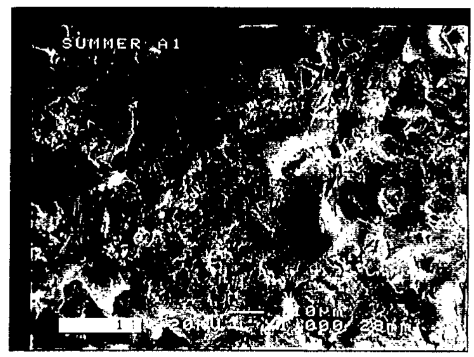

Plate 11: Summer Site

Plate 12: Winter Site

C1 Horizon Grey Brown Silt, 40 cm beneath surface

Optical Microscope *(frames are 12 mm wide)*

SEM

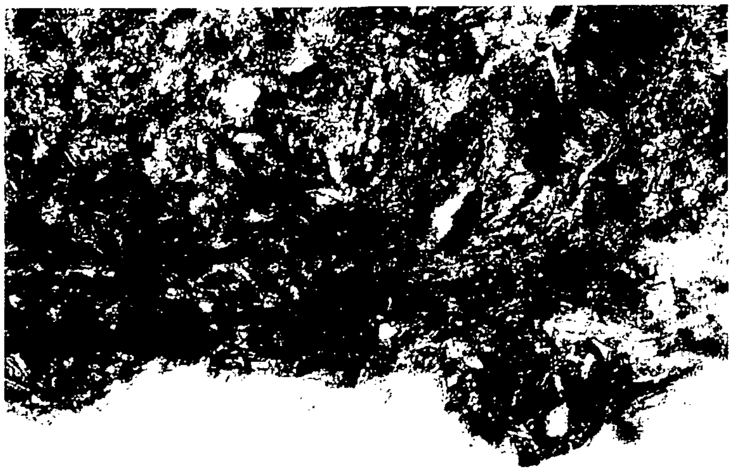

Plate 13: Control Site

Plate 16: Control Site

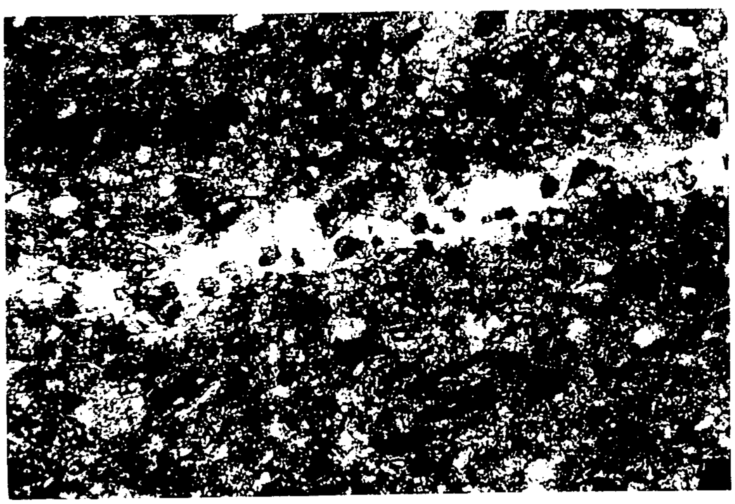

Plate 14: Summer Site

Plate 17: Summer Site

Plate 15: Winter Site

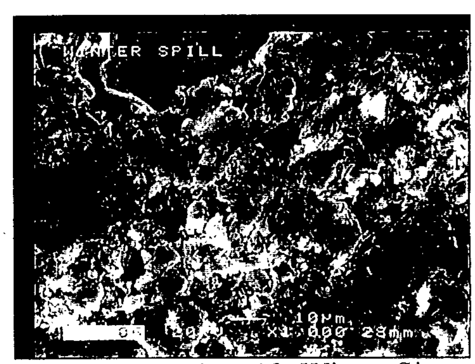

Plate 18: Winter Site

Aggregation of Contaminated Silt

Optical Microscope *(frames are 3 mm wide)*

Plate 19: Control Site

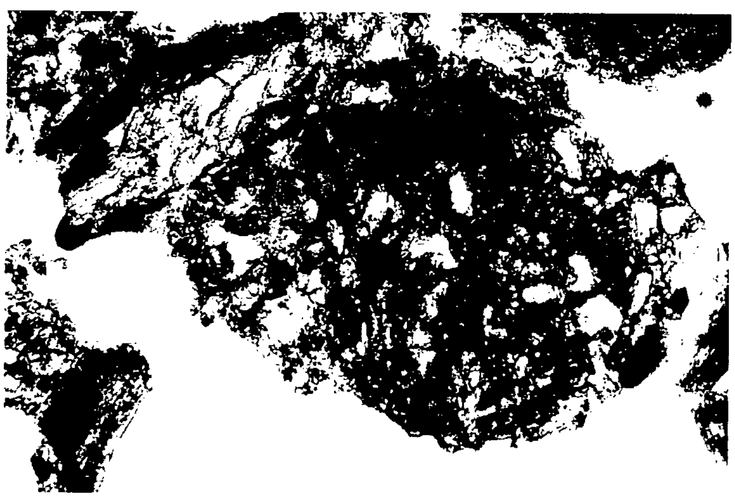

Plate 20: Winter Site

SEM

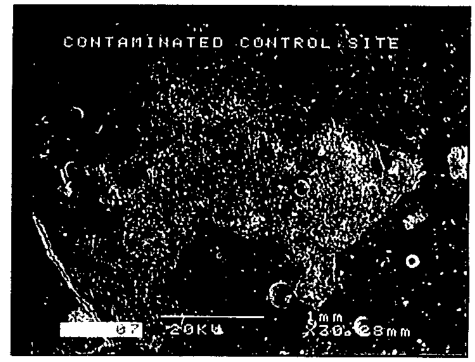

Plate 21: Control Site

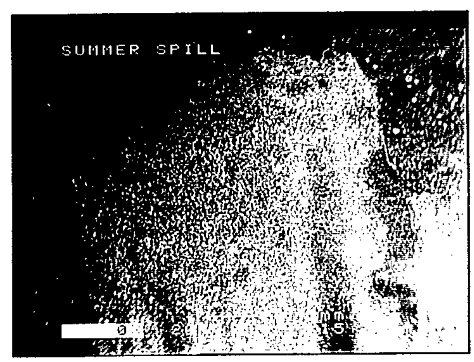

Plate 22: Summer Site

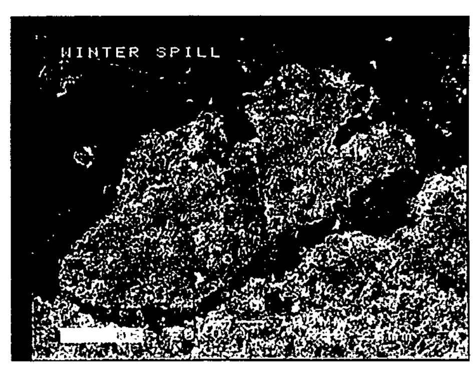

Plate 23 Winter Site

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Report: Microstructural alteration of hydrocarbon-contaminated permafrost-affected soils at the Caribou - Creeks CRREL research watershed: Implications for subsurface transport

5. FUNDING NUMBERS
N68181-98-M-5736

AUTHOR(S)
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3. ABSTRACT (Maximum 200 words)

The thermodynamic conditions within the seasonally frozen active layer overlying permafrost in the Caribou - Poker Creeks Research Watershed in Alaska are such that there is continuing translocation of water and ice, and the displacement of soil particles. The introduction of immiscible hydrocarbon compounds from two large scale winter and summer experimental crude oil spills into this dynamic porous medium results in mocrostructural changes that take place as a function of cryogenic process and contaminant concentration. Optical and scanning electron microscope observations reveal evidence of changes in soil morphology. Reorganisation of silt and clay size minerals and organic particles has resulted in changes in aggregation and interaggregate porosity in the histic pergelic cryaquest. The degree of interaggregate porosity increases as a function of hydrocarbon concentration, specifically volatiles and as a function of the soil profile. Hydrocarbon concentrations were observed to decrease as a function of depth in the O1, A1 and C1 horizons for all the sites, including the selected control site situated between the winter and summer experimental oil spills. The modifications of the microstructure change macroscopic properties (thermal, hydraulic, and mechanical), and this leads to modifications in terrain which become more marked over years. Remote sensing techniques will be important in the prediction and verification of contaminant movement.

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UNIVERSITY OF CAMBRIDGE, U.K

B. REPORT TITLE AND/OR NUMBER MICROSTRUCTURAL ALTERATION OF HYDROCARBON-CONTAMINATED PERMAFROST-AFFECTED SOILS AT THE CARIBOU-CREEKS

C. MONITOR REPORT NUMBER
R+D 8594-EN-01

D. PREPARED UNDER CONTRACT NUMBER
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